U.S. DEPARTMENT OF COMMERCE
National Technical Information Service
PB-295 038

A Survey of Packaging for Solidified Low-Level Radioactive Waste

Battelle Columbus Labs, OH

Prepared for

Office of Radiation, Washington, DC Technology Assessment Div

Sep 78

United States
Environmental Protection
Agency

Office of
Radiation Programs
Washington DC 20460

Technical Note
ORP/TAD-78-1
September 1978

Radiation

PB 295038

EPA

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SPRINGFIELD, VA. 22161

BIBLIOGRAPHIC DATA SHEET	1. Report No. ORP/TAD-78-1	2.	3. Recipient's Accession No. PB295038
4. Title and Subtitle A Survey of Packaging For Solidified Low-Level Radioactive Waste			5. Report Date 6.
7. Author(s) Neil E. Miller (Editor)			8. Performing Organization Rept. No.
9. Performing Organization Name and Address Battelle-Columbus Laboratories 505 King Avenue Columbus, Ohio 43201			10. Project/Task/Work Unit No. 11. Contract/Grant No. EPA No. 68-01-3924
12. Sponsoring Organization Name and Address U.S. Environmental Protection Agency Office of Radiation Programs Washington, D.C. 20460			13. Type of Report & Period Covered 14.

15. Supplementary Notes

16. Abstracts

There are presently no federal regulations controlling the packaging of low-level radioactive wastes for disposal by shallow land burial. The packaging of low-level radioactive wastes for ocean disposal by the European community has been controlled by guidelines of the Nuclear Energy Agency of the OECD. For both methods of disposal, the 55-gallon steel drum has been the most commonly used container. The use of nonmetal packaging has been more common for contaminated trash and other low-level wastes at DOE shallow land burial sites. The life of the disposal container is affected by the structural stresses imposed by the handling and disposal operations, and by deterioration from corrosion in the disposal environment.

17. Key Words and Document Analysis. 17a. Descriptors

Low-Level Radioactive Waste Packaging
Disposal Containers
Corrosion
Radiological Effects
Environmental Analysis

17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report) UNCLASSIFIED	21. No. of Pages 46
	20. Security Class (This Page UNCLASSIFIED	22. Price PCA03 / MF A01

FORM NTIS-35 (REV. 10-73) ENDORSED BY ANSI AND UNESCO. THIS FORM MAY BE REPRODUCED USCOMM-DC 8265-P74

TECHNICAL NOTE
ORP/TAD-78-1

A SURVEY OF PACKAGING FOR SOLIDIFIED LOW-LEVEL RADIOACTIVE WASTE

September, 1978

This report was prepared as an account of work sponsored by the Environmental Protection Agency of the United States Government under Contract No. 68-01-3924.

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PREFACE

The Office of Radiation Programs of the U. S. Environmental Protection Agency carries out a national program designed to evaluate human exposures to radioactivity, and to promote development of controls necessary to protect the environment and public health from such radioactivity. An important part of this program consists of the development of environmental protection criteria and standards for radioactive waste managememt and disposal.

To further this program, studies have been supported by EPA to survey and evaluate the environmental adequacy of the state-of-the-art of the packaging of solidified low-level radioactive waste for shallow-land burial and ocean disposal.

Readers of this report are encouraged to inform the Office of Radiation Programs of any omissions or errors. Comments or requests for further information are also invited.

David S. Smith
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ABSTRACT

There are presently no federal regulations controlling the packaging of low-level radioactive wastes for disposal by shallow land burial. As a result the regulations of the U.S. DOT for the packaging of radioactive materials for shipping have been a major influence in packaging for this method of disposal. Ocean disposal of radioactive materials has not been practiced in the United States for a decade. The packaging of low-level radioactive wastes for ocean disposal by the European community has been controlled by guidelines of the Nuclear Energy Agency of the OECD. For both methods of disposal, the 55-gallon steel drum has been the most commonly used container. The use of nonmetal packaging has been more common for contaminated trash and other low-level wastes at DOE shallow land burial sites. The life of the disposal container is affected by the structural stresses imposed by the handling and disposal operations, and by deterioration from corrosion in the disposal environment. Whereas data show that steel drums may be penetrated by corrosion in some soils or sea water in 2 to 4 years, inspection of drums after disposal has shown a range of lifetimes from a few years to a decade or more. The coatings presently used on drums are ineffective because of defects which occur during handling and disposal operations. The radiation exposure to concrete, bitumen, or polymeric solidification media by the incorporation of typical low-level radioactive wastes is not expected to cause significant structural damage to the waste form. Longer container life may be achieved by improving the structural strength of the containers to withstand the stresses applied by handling and disposal operations and by increasing the compatibility of the container with the interior and exterior environments. A thorough systems study of the roles of the disposal environment, the waste form, and the waste container in restricting the transport of radionuclides from the disposal area is needed to show the cost-effective benefits to be gained from improved container integrity.

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1.0 INTRODUCTION

The disposal of radioactive wastes has become a key issue in the development of the nuclear power industry. Since the early years of nuclear technology many of the wastes have been disposed of by shallow land burial and ocean disposal. As the technology has advanced there has been a growing awareness of the need to improve the management of nuclear wastes to protect the present and future environment of man. To this end, many facets of nuclear waste management are being studied to develop the information base for the formulation of criteria and to define specific needs for research and development.

This study was conducted for the United States Environmental Protection Agency by Battelle's Columbus Laboratories to assist in defining the role of packaging in the disposal of low-level radioactive wastes by shallow land burial or ocean disposal. In this study a literature search was conducted from which a summary of the state of the art of packaging for low-level waste disposal was prepared. This report also contains a discussion of effects of the disposal environment upon the life and integrity of the packaging. From this information recommendations are made for further improvements in the packaging as a containment for the radioactive wastes.

2.0 STATE OF THE ART OF PACKAGING FOR DISPOSAL OF SOLID LOW-LEVEL RADIOACTIVE WASTE BY SHALLOW LAND BURIAL OR OCEAN DISPOSAL

2.1 Background

To place this brief review in perspective it is desirable to define the title to minimize the ambiguity that may exist concerning its terms. There has been a gradual evolution of the state of the art of packaging since the need for disposal of radioactive waste began in the 1940's. To be of most benefit the art in practice during the past five years is the objective of this discussion. It is most common to describe the packaging for radioactive materials where the term packaging refers to one or more wrappers or containers and their components such as structural members, shielding, and seals. A package refers to the packaging and its contents, in this case the waste. However, when considering the retention of wastes after disposal the performance of the packaging can also be influenced by the contents as well as the disposal environment thus in the broader view it is prudent to include both packaging and typical contents.

There is no generally accepted definition of "low-level radioactive waste" as there is for "high-level waste". Often "low-level waste" is used synonymously with "low specific activity" or "low radiation level". This is confusing as all radioactive waste except "high-level waste" may be properly identified as "low-level waste". Since 1970 wastes contaminated by transuranic elements at levels in excess of 10 nanocuries per gram (referred to as TRU wastes) have not been accepted for disposal at AEC (now DOE) shallow land burial sites. Rather, they are placed in 20-year retrievable storage for ultimate disposal in a Federally operated repository which is to be constructed at some future time. Five of the six commercial low-level radioactive waste burial sites have followed this example and do not accept TRU waste for burial. Thus where the disposal by land burial is concerned it is logical to assume that TRU wastes are not included. Also, by nature of their large volume and low specific activity the tailings from uranium and phosphate ore operations are

not considered for disposal in shallow land burial sites. Therefore, for this application "Low-Level Wastes" (LLW) are those wastes other than those specifically categorized as high-level and TRU wastes or mine and mill tailings. As implied by the definition, LLW varies in its source, physical, chemical, and radiological properties and ranges from slightly contaminated paper wipes and coveralls to highly activated structural components of nuclear power reactors. The wide range of properties of LLW could be illustrated as below:

- Physical form: trash, laboratory animals, ion exchange resins, evaporator sludges, filters, sorbed and solidified liquids, sealed sources, reactor parts, parts of buildings and structures
- Chemical form: soluble salts, insoluble materials, cleaning solutions, acidic solutions, basic solutions, complexing agents, and organic compounds
- Radioactivity: levels range from those with barely detectable or no detectable activity, to those with activity levels high enough to require shielding for transport and handling
- Sources of waste: hospitals, research institutions, universities, commercial manufacturers, Federal facilities and nuclear power production facilities.

The LLW waste form will be a dry solid or excess liquid will be chemically or physically immobilized in a suitable matrix such as concrete, or an adsorbent such as vermiculite.

The disposal of radioactive wastes during the war years of 1941-1945 was conducted by burial at the site at which they were produced.[1,2] Fortunately the quantities were small, the transuranics were carefully conserved for their own value, and the separated fission products were not a serious problem. In the post-war period as nuclear research and development expanded, the increased quantities of radioactive waste and contaminated equipment forced attention to the disposal problem. In the United States new burial grounds were selected with greater care at AEC sites and many old sites were no longer used. Some wastes produced by

commerce and industry were accepted for burial at AEC sites, but the majority was buried at sea by private companies. From 1962 through 1971 six commercially operated burial grounds began operation. In the late 1960's, although not prohibited, the practice of sea disposal was phased out. Through 1976 it is reported that over 4.2×10^5 m^3 of low level waste initially containing 3.9×10^6 curies of byproduct material have been buried at commercial sites[3] and it is estimated that 1.5×10^6 m^3 has been buried at DOE sites.[4] Approximately 95,000 Ci[5] of waste were buried at three dumping sites off of our Atlantic and Pacific coast lines.

In Europe, the scarcity of suitable land for burial sites has led to the practice of sea disposal. Between 1951 and 1966 the United Kingdom disposed of 40,000 Ci of waste in the Atlantic Ocean. From 1967 through 1976 approximately 29,400 Ci of wastes were dumped by various European countries under the control of the Nuclear Energy Agency of the Organization for Economic Cooperation and Development.[6]

2.2 Packaging for Low-Level Radioactive Waste for Shallow Land Burial

There are presently no Federal rules or regulations which specify the packaging to be used for shallow land burial of radioactive waste. To the present time there is no credit given to the packaging for the retention of the radioactive products after the package is buried. The packaging is intended to protect the personnel handling the waste and the general public from unnecessary radiation exposure by direct radiation or by transferable contamination from the time the waste is packaged until it is buried. To meet this objective the packaging has been controlled by the rules of the waste-generating facility, the regulations for transportation, and the rules of the operators of the burial ground. It is possible that one organization can perform all of these functions and be the only control over the packaging. Usually this is not the case. The waste-generating site may have a government, an industrial, or a commercial operator which may package the waste or may engage another company to perform the service. The transportation of the radioactive material may be controlled by Federal, state or local rules and regulations.

The burial grounds may be operated under contract to DOE or by commercial operators. Of these, the greatest influence on the packaging is exercised by the rules and regulations of the U.S. Department of Transportation for transportation of hazardous materials, 49 CFR 170-199.(7) The licensing of packages for shipping radioactive materials is controlled by the regulations of the U.S. Nuclear Regulatory Commission in 10 CFR 71.(8)

The regulations for the packaging for the transport of radioactive materials are dependent upon the type and quantity of materials to be shipped. Some low-level wastes may be classified as low specific activity (LSA) material as defined in 49 CFR 173.389. These wastes only require strong, tight, industrial shipping packaging when shipped by sole use vehicle. When shipped by common carrier LSA materials must be shipped in DOT-approved packaging. In either case the radiation-dose limits of 49 CFR 173.393 apply as they do for all other types of packaging.

Other categories of radioactive materials are Type A, Type B and "large quantity" as defined in 49 CFR 173.345 and 173.389. The allowable quantity in each category is related to the nuclides to be transported. For this purpose most nuclides have been classified into seven transport groups according to their relative hazard, Transport Group I being most hazardous. For example, for Type A quantities most of the classified nuclides are limited to a total not to exceed 20 curies. However, many other nuclides, including the common waste products Co-60 and Cs-137 are not to exceed a total of 3 curies. Most nuclides of heavy metals and those with very long half-life are limited to a small fraction of a curie. Type B quantities are nominally a factor of 10 or more greater than Type A, and most waste products would be permitted in quantities as great as 200 curies. "Large quantities" are those that exceed Type B quantities.

The packaging for the shipment of Type A quantities must meet the DOT specification 7A for Type A general packaging, 49 CFR 178.350. Prior to 1976 a large variety of DOT approved Type A containers were listed in 49 CFR 173.395 including metal and fiber drums, and fiber and wooden boxes in a range of sizes. Specifications for each are given in 49 CFR 178. The specifications list size, configuration, type and thickness of materials of construction, type of closures, pre-use testing, limitation on contents,

and external markings. Other Type A packaging available includes steel and concrete bins and shielded containers. Beginning in 1976 the paragraph 173.395 was modified to delete approval for specific containers and now gives approval only for containers meeting the general 7A specification. However, this paragraph had a large affect on the state of the art of containers, particularly in the use of DOT Specification 17H steel drums.

Type B quantities and large quantity shipments must use a DOT specification 6M container or specially approved Type B containers. Approval of these containers and a Certificate of Compliance may be received from the NRC by compliance with the regulations in 10 CFR 71.

The most common container used for packaging low-level wastes for disposal by shallow land burial is the steel drum. The 55-gallon drum is most common but 30-gallon and smaller are also used. These are usually painted on all surfaces for corrosion resistance and for some applications plastic bags or rigid liners are used for additional containment. Steel drums are relatively inexpensive, easy to load and handle, and have been acceptable for disposal at all burial grounds. DOT-approved steel drums serve as Type A packaging for the shipment of Type A quantities and LSA waste. The wastes can be loaded into the drums at the waste collection area, the drums shipped by common carrier to the disposal site, and the drummed waste can be placed directly into the burial trench. Where radiation levels must be reduced to meet DOT external dose rate requirements a concrete liner or other suitable shielding material may be placed in the drum within the weight limitation of the drum. Wet wastes which require solidification prior to disposal are often mixed with a solidifying agent, such as cement or urea formaldehyde resin, and cast directly into a drum. Often the drum is used as a receptacle into which loose trash is compacted prior to disposal. Dewatered ion exchange resins and sludges are loaded directly into drums at some sites but these have not been acceptable for disposal at all burial grounds because of their moisture content.[9] For some highly mobile wastes, such as tritium, it is common practice to utilize a sealed inner metal or plastic liner, or a polymeric sealed concrete matrix within the outer metal drum as an additional barrier for the containment of the waste.

Steel drums are also utilized as packaging for Type B or larger and high-radiation-level Type A quantities of radioactive wastes where the drum does not qualify as a shipping package. In this case the drums are shipped in an overpack which serves as the approved shipping container. For example unshielded Type B overpacks are available which can hold 42 55-gallon drums for transport by truck, rail, or cargo vessel. Shielded Type B overpacks are typically smaller in size and capacity so that the total weight does not exceed the limits for truck shipments. When delivered to the burial ground the drums are withdrawn from the Type B container and placed into the burial trench; the shipping container is returned for reuse.

Larger metal containers have found increased use where large volumes of waste products must be disposed of on a routine basis. It has been found more economical to use containers with ten or more times greater capacity than the 55-gallon drum. Waste packages of this size must be shipped in an overpack so the containers are designed as disposable liners for specific DOT-approved shipping containers. These large containers are commonly used for shipping used ion exchange resins from commercial power reactors. Low activity resins may be shipped in 160 to 180 ft^3 liners in an overpack with shielding equivalent to 2-in. of lead. Resins with a higher specific activity, may qualify as Type B or large quantities and be shipped in 70-ft^3 liners which require an overpack with shielding equivalent to 4-in. of lead. These large metal containers are made in a cylindrical configuration of carbon steel with welded seams. The containers have a relatively thin (nominally 1/4-in) wall and are equipped with lifting lugs and fittings for filling, venting, and removing water.

Nonmetal packaging is being utilized for trash with low levels of contamination.[2] One DOE laboratory disposes of the majority of its loose trash by sealing it in plastic bags which are then placed in cardboard boxes or small fiber drums.[10][11] Another DOE laboratory compacts solid low level waste into 14 ft^3 bales contained in plastic lined fiber board boxes.[12] At both sites these waste packages are buried in an onsite shallow land burial area. Another DOE laboratory packages low-level waste for disposal in DOT 7A plywood boxes with PVC or fiberboard liners.[13]

These waste packages are shipped off-site for disposal at another DOE shallow land burial site. Cardboard boxes are not acceptable packaging at most commercial burial grounds and non-metal packaging for commercial sites is limited to less frequently used DOT approved non-metal packaging.

2.3 Packaging for Low Level Radioactive Waste for Ocean Disposal

The current state of the art of packaging of radioactive waste for ocean disposal is established by practices of the European community. The Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development has published guidelines for packaging of wastes for ocean disposal which cover the design, manufacture, assembly, handling and transport of the packages.[14] The packaging is to be designed to assure adequate containment of the waste during handling and transport until the end of the disposal operations. The package should have adequate shielding to allow safe handling during all phases of the operation. The package and any inner containers should have a specific gravity of not less than 1.2 to assure sinking to the sea bed. Also, the package should have adequate strength to maintain its structure, or to have a pressure equalization system to assure that the packaging will retain its contents for an indefinite time after reaching the sea bed.

The guidelines describe two general type of packages, a monolithic design and a multistage design. In the monolithic design the waste is incorporated into a solid mass with no significant voids. The monolithic block provides a rigid inner structure which strengthens and supports the packaging during handling, transport, and submersion. An example of this is waste mixed with concrete or bitumen and cast into a steel drum without any significant internal voids. The solidified block acts as an incompressable support for the drum wall and heads. The multistage design has multicomponent assembly and may contain significant internal voids which require a pressure equalization system to prevent structural failure of the packaging during submersion. An example of this is compacted, contaminated trash bundles placed in a concrete liner in a steel drum; a penetration with a check valve would allow pressure equalization as the package is submerged. The

packaging is the steel drum; the concrete liner serves as shielding but does not necessarily provide adequate structural support for the drum during submersion. A monolithic package needing additional shielding can be placed in a concrete overpack, or a concrete-lined steel overpack converting it into a multistage design.

The NEA guidelines have recommendations for construction as well as radiation levels, surface contamination limits, criticality control, weight limitations and markings.

In the United States, EPA has authority over ocean disposal including low-level radioactive wastes, and the regulations[15] address containerization of wastes. However, since ocean disposal of radioactive wastes has not been practiced in this country for a decade, the regulations have not influenced the current state of the art.

3.0 EFFECTS OF THE DISPOSAL ENVIRONMENT ON THE LIFE OF WASTE PACKAGING

3.1 Deterioration of Containers by Corrosion and Decomposition

Penetration of metal containers by corrosion is one of the failure modes that can result in breaching of the container. Failures from corrosion evolve slowly (months to years) and total area penetrated may also grow slowly, i.e., the lateral growth of a pit. Both ocean disposal and soil burial environments can be corrosive to the external surface of steel containers; moist contents of the containers can lead to corrosion to internal surfaces, particularly if acid constituents are present. Containers of wood, fiberboard or cardboard will suffer from rapid deterioration depending upon soil condition.

Metal Corrosion by Soils

The characteristics of soils for burial sites have been described by Romanoff[16] and Columbo and Neilson[17].

In general, the corrosiveness of soils is rated by the specific resistivity of the soils which, in turn, is a rough measure of the soluble ionizable salts in the soil. Typical ranges are:

Corrosivity	Resistivity, ohm-cm
Very	<500
Fair	500-2,000
Mild	2,000-20,000
Little	>20,000

However, severe pitting has been observed in 100,000 ohm-cm soil, so that resistivity alone cannot accurately predict corrosivity, but can serve as a general guide.

Because of the complex nature of soils, this corrosivity can vary widely. At this time, it is not yet possible to predict corrosivity based on soil analyses alone. In fact, similar soils from different locations in

the United States may have vastly different corrosive tendencies. Concentrations of trace chemicals and organic matter can vary widely and, since these are not considered in normal analyses, can account for the wide ranges of corrosivity.

In the projected applications, conventional 55-gallon steel drums are being considered. These normally are coated on the exterior with a thin lacquer finish. If undamaged, this type of coating affords protection in soil burial.[18] However, this finish is subject to chipping and abrasion when handled, so that it must be assumed that all buried containers will have holidays (bare spots) in their external coatings.

Coatings are applied for their protective qualities. However, in the case of underground burial, coatings often accelerate pitting. For example, it has been observed that bare pipelines buried in a mildly corrosive soil may start to perforate after 10 to 12 years' service whereas coated pipelines with no additional protection might perforate in 5 to 6 years. In part, this is the result of long-range galvanic effects over considerable spans of pipeline, which would not be expected to be so severe over the relatively short distances involved with individual electrically isolated 55-gallon drums. However, the coating itself frequently is cathodic to the exposed metal so that a strong galvanic driving force exists between the large cathodic surface area of the coating and the small anodic area of bare metal at holidays. This condition can lead to rapid pitting at the small bare areas.

Not only does handling break the lacquer film on the drum, but denting can cause increased corrosion of the steel. Work performed at Los Alamos has shown an increased rate of corrosion at stressed areas resulting from minor damage such as denting.[19]

Thus, in considering the performance of buried lacquered drums with holidays, it must be assumed that they will probably perform no better in the burial environment than bare steel with respect to penetration by pitting. However, overall corrosion (metal loss) would be expected to be less on the lacquered drums.

At first glance, a small pit through a container might not be considered to be a serious problem since migration of the contents into the soil would depend on diffusion outward through the hole via a liquid or gas phase.

However, if a liquid penetrates the container, the same slow diffusion processes can be expected to contribute to the enlargement of the pit and increased attack on the inside of the drum. This would be particularly true where the soil is well aerated. Inside the drum, the oxygen supply would become depleted in the liquid because of the slow diffusion through the small hole. This would result in a galvanic cell with the depleted oxygen region being the anode (corroding area) while the well-aerated external surface would be the cathode (noncorroding area). Thus, once the container is penetrated by a pit, its deterioration by corrosion can be accelerated.

The corrosive characteristics of a number of soils have been determined on bare steel pipes in studies conducted by Romanoff[16] Corrosion data are presented for some seventy soils. Corrosion rates varied from 0.06 mil/yr for gravelly sandy loam to 6.0 mils/yr in high-alkali clay; corresponding maximum pit depths for these two soils were 20 mils in 17.5 years and >251 mils in 4 years, respectively. As indicated earlier, predictions of corrosion performance from known behavior in a given soil to that in a similar soil are frequently not reliable. Nevertheless, corrosion data from Romanoff for steel pipe buried in soils with conditions similar to the present shallow land burial sites in the United States show maximum pit depths of 40 mils or greater in 2 years. This indicates that steel drums buried in similar soils may be penetrated by pitting in a few years.

Corrosion by Seawater

Seawater is more uniform in composition than soil at various locations on the earth. Nevertheless, the corrosivity of seawater can vary depending on oxygen content, marine life, temperature, and contamination. Dissolved oxygen content is the most critical variable in corrosion by seawater. Corrosion under the conditions of neutral to very slightly alkaline salt solutions is dependent on the availability of oxygen to depolarize the cathode reaction. Thus, in general, as oxygen content increases, the corrosion rate increases. Furthermore, oxygen concentration cells are very active in seawater, because of the high conductivity of the medium. Thus, a small deposit of sand or an occasional marine growth can result in rapid pitting

because of oxygen depletion beneath the covered area as explained earlier. Steel components partially embedded in mud would corrode below the mud line for the same reasons. It is true that the dissolved oxygen concentration at depths is lower than on the surface, but the oxygen concentration does not necessarily decrease progressively with depth. For example, oceanographic data obtained at a site west of Port Hueneme, California, reveal a rapid decrease in dissolved oxygen from ∿6 ppm at the surface to ∿0.2 ppm at 2000 feet, but with a subsequent gradual increase to ∿1.5 ppm at 5600 feet.[20]

Biological activity, as mentioned earlier, can promote pitting and reduce oxygen levels where large quantities of biota live (and die) in relatively shallow waters.

Temperature has a complex effect on corrosion. An increase in temperature normally increases chemical reaction rates and increases biological activity, both of which will increase corrosion attack. On the other hand, an increase in temperature decreases oxygen solutility and causes increased precipitation of calcium carbonate and magnesium hydroxide as calcareous scales. Both phenomena can increase resistance to corrosion attack.[21]

The corrosion rate and pitting rates of steel in seawater decrease with time. The overall general corrosion rate in shallow water drops to ∿5 mil/yr after 1 year, but does not go much below 3 mil/yr with continued exposure beyond 1 year.[22,23] In these same studies, the pitting of carbon steel averaged ∿60 mil penetration after 4 years and ∿85 mil after 16 years.[23] Maximum pit depth was 155 mil after 16 years.

At depths, of the order of 5600 feet, the overall corrosion rate of steel is ∿1 mil/yr or about one-third that at the surface.[20] However, pitting rates at depth, particularly in crevices, are not greatly different from those at the surface. Since most ocean disposal is expected to be at great depths, say not less than 13,000 ft, one could expect a conventional 55-gallon drum to perforate by pitting at holidays in the coating as rapidly as 4 years.

Corrosion by Contents of the Container

Corrosion of the inside of the steel drums by the contents is also a possible mode of perforation. In general, the inside surface will not be corroded if moisture is absent (relative humidity <70 percent). If a liquid phase is present, the extent of corrosion can be controlled by adjusting the pH of the contents (prior to closing) to pH 10-11, the optimum pH for the resistance of steel to attack.[24] However, certain plastics such as polyvinyl chloride (PVC) can degrade by radiolysis[25] or heat (>70 C) to form HCl which, in turn, would attack the inner steel surface.

Increasing the pH to 10-11 may not be effective if the drum can breathe so that it has access to a fresh air supply. Under these conditions, neutral or alkaline chloride solutions can promote pitting in much the same manner as in seawater, because there is an ample supply of oxygen to depolarize the cathodic reaction in the corrosion process. On the other hand, if the drum is airtight, the oxygen supply would soon be exhausted, and the corrosion attack would be stifled. The effects of increasing the pH may not be of long duration if radiolysis of the contents can produce acidic products.

Discussion of Corrosion of Metal Containers

It is readily apparent from the preceding discussion that perforation of 55-gallon steel drums by corrosion of the external surface is a strong probability in either land or ocean disposal unless extra precautions are taken. (Perforation due to corrosion by the contents is also a possibility, but may be controlled to a reasonable level by appropriate measures.) Conversely, individual drums may survive burial or an entire burial site may not be corrosive. Unfortunately, corrosivity cannot be predicted with any degree of consistency in soils and, similarly, the conditions that limit corrosion in seawater--such as complete biological fouling or buildup of calcareous deposits--also cannot be predicted. Thus, relatively long-term corrosion studies are needed at each burial site (including the deep ocean) to develop a predictive capability.

Of course, extra protective measures can be employed. For external corrosion, these would consist of thicker, more resistant, and more tenacious

coatings plus sacrificial anodes such as zinc. Even under these conditions an occasional failure may occur when anodes are broken loose because of rough handling, when anodes are rapidly consumed because of large exposed bare areas on the external portion of the drum, or when anodes become completely covered with heavy biological fouling.

For soil burial, a heavy plastic cover over a number of drums supported on a pad may effectively reduce corrosion, but, again, 100 percent integrity cannot be assured because of damage during handling operations and uncontrolled factors such as shifting of the soils while settling.

Controlling corrosion by the internal environment can be effectively carried out if proper control can be maintained over the packaging operation. Depending on the severity of the corrodant, a number of measures can be taken, such as: dry packaging with desiccant to minimize moisture; volatile amine vapor phase inhibitors for high-humidity, low-corrosivity conditions; neutralization and pH adjustment to 10-11 for liquid environments; and heavy linings for liquid environments, but avoiding PVC or other unsaturated chlorinated polymers to preclude HCl generation by radiolysis.

In conclusion, breaching of the steel drums can be minimized by using protective measures (in addition to the usual lacquer on the drums), that are tailored to the specific environments inside and outside the drums. However, 100 percent integrity probably will never be achieved because the drums must be handled by mechanical means, and once buried, are at the mercy of the stresses of soil movement or ocean currents.

Decomposition of Wood Containers in Soil

The decomposition rates of wood are determined primarily by three conditions: (1) the temperature-moisture regime; (2) characteristics of woody material; and (3) population density of decomposing organisms, especially orthropods. Storage of materials in wood containers in soil can be expected to be effective for a finite time period (5 to 25 years) depending on the three sets of conditions listed above [26].

There are two major modes of wood decomposition in soil: linear wood degradation and logarithmic degradation rates. Linear wood degradation

rates are the initial stages of breakdown. Under high soil moisture conditions and temperatures >4 C, a rate of 1 to 8 percent loss over a period of a year can be expected. During this time, carbon is selectively lost from wood while nitrogen, phosphorus, and other nutrients are accumulated. When nutrients have accumulated to a threshold level, decomposition rates of wood will increase rapidly and may approach a logarithmic function for a finite period of time, 6 to 12 months, until nutrient supplies are exhausted.

In general, wood decomposition rates are stimulated by:

Temperature-moisture regimes[27]

- Minimum freezing conditions
- Moisture >50 percent dry weight in soil
- Constant moist conditions.

Characteristics of woody materials[28,29]

- Low density
- High homogeneity of wood types used in materials such as particle board
- Detectable nitrogen and phosphorus concentrations
- High water holding capacity.

Population density of decomposing organisms

- Presence of arthropods which colonize wood, e.g., termites, ants, psalid beetles, dipteran larvae[30]
- Presence of fungal and bacterial populations which colonize cellulose substrates[31].

It is possible to attenuate wood decomposition rates by using materials of diverse wood types, impregnated with creosote or other high-molecular-weight organics, and burial at depths greater than the normal "biotic" zone of the soil. Choice of soils which are well-drained, nutrient depleted, and droughty will also allow longer stability of wood containers.

3.2 Effects of Radiation Damage to Waste Packaging

The radiation damage to solidified low-level wastes is of interest for several reasons. The decomposition products are generally gaseous and can cause internal pressurization of the waste containers or may produce explosive mixtures within the containers. Some decomposition products may be corrosive and affect the container life. Radiation damage may cause a deterioration of the solidifying or fixation agent, making the radioactive species more susceptible to transport.

At present, information is insufficient to make a quantitative assessment of all of the radiation effects on solidified wastes. However, the current literature shows some progress is being made particularly in reference to the gas release and equilibrium pressures anticipated for particular wastes. The following discussion is intended to place the problem in some perspective.

Commercial light water power reactors can be expected to be a major source of low-level wastes in the future. The liquid wastes from reactors are concentrated and appear as evaporator bottoms, filter sludges, or ion exchange resins. They are generally consolidated in one of several forms for disposal. The most common solidifying agents are usually based on cement or plaster, a polymer such as urea formaldehyde, or bitumen.

Effect of Composition

To qualitatively predict the radiation effect (damage) on the waste composite due to incorporated radionuclides, it is necessary to know the composition, the amount of various isotopes, and size and geometry of the container. All of these can and do vary from one waste form to another. For instance, the properties of bitumen vary depending on grade, as does a composite based on a cement. The solidified waste composition also varies with the amount and kind of waste incorporated, i.e., filter sludges, evaporator bottoms, etc. However, for this general discussion the following observations can be made. The radiation dose to the solid waste is a function of its density and its radiation absorption coefficient. Most of the waste forms of

concern are composed largely of the lighter elements, hydrogen, oxygen, carbon, silicon, magnesium, aluminum, calcium, etc. Thus, the overall mass absorption coefficient will not vary greatly from one form to another. Nor does the density of the waste forms vary greatly. Thus, for this approximation, an average absorption coefficient and density were assumed for all waste forms of interest.

Radiation Source and Estimated Dose

The kinds and amount of radionuclides vary with the nature and origin of the waste. As a basis for estimating a typical radiation source term one published[32] tabulation of concentrations of radioactive materials in solid wastes from light water reactors has been utilized. Although tritium is shown to be abundant in these wastes, from the standpoint of radiation effects, it is a small source of absorbed energy (the emission is a very weak beta). Several other isotopes can also be disregarded even though they represent several percent of the radionuclides produced. For example, Cr^{51} has a short half-life and Mn^{54} has a low total energy. From the standpoint of radiation effects, three isotopes provide most of the energy, Co^{60}, Cs^{137}, and Cs^{134}. For this study, it was assumed that these three isotopes formed a representative radiation source for low-level wastes. Gamma radiation is the major source for these three isotopes but the accompanying betas make a significant contribution to the absorbed dose rate.

In estimating the absorbed dose rate, it is assumed that all the beta energy is absorbed. To estimate the dose rate from the gammas an expression for self-generating, self-absorbing infinite cylinder was used[33]. The diameter of the cylinder was taken to be that of a 55-gallon drum and the activity of the composite was assumed to be 4.7 $\mu Ci\ g^{-1}\ Co^{60}$, 3.3 $\mu Ci\ g^{-1}\ Cs^{137}$, and 2.00 $\mu Ci\ G^{-1}\ Cs^{134}$. This represents a typical total specific activity and a distribution of the three isotopes as they would be expected to be formed in light water reactors.

Radiation Effects

There is little quantitative information on the acceptable radiation dose to the different waste forms. For example, for bitumen, the dose at which radiation damage becomes significant is reported to be in the range of 10^8 to 10^9 rads. Holcomb[34] states that depending upon the type of bitumen, doses of 10^8 rads from internal radiation are acceptable. Sousselier[35] states that doses to 10^9 rads are required for significant radiation damage.

Colombo and Neilson[36] have studied the gamma irradiation of cement, urea-formaldehyde, and bitumen at exposures from 10^5 to 10^9 R. They report that the radiolytic gas generation from all three matrix materials is a function of exposure rate. They observed that the gas production increases at a given exposure as the exposure rate decreases. However, for a given exposure time, the higher exposure rate generally resulted in a larger gas release. The quantity of gas evolved per unit energy input, G value, to the urea-formaldehyde matrix was an order of magnitude greater over the exposure levels from 10^5 to 10^8 R than that of cement. G values for bitumen were not obtained at the lower exposures, but at 10^7 and 10^8 R, the values for bitumen were significantly less than for cement. However, at 10^9 R the G value for bitumen was greater than those of cement and urea-formaldehyde which may indicate a threshold for more rapid deterioration.

Work reported by Bibler and Orebaugh[37] shows the effects of dose rate and total dose on the gas production during the irradiation of concrete by gammas from cobalt-60 sources. The gas produced is predominantly hydrogen from the radiolysis of water. They observed that the calculated number of hydrogen molecules produced per unit of energy absorbed in the concrete, G value, was constant and independent of dose rate over the range studied. Thus it is believed that the data can be related to the lower dose rates typical of low-level wastes. When the irradiation of concrete was conducted in a closed system, it was observed that in time an equilibrium pressure was reached and the pressure was proportional to the dose rate. This indicates the presence of a competing reaction for the removal of hydrogen. Below 10^4 rads/hr the equilibrium pressure was insignificant; at 10^5 rads/hr approximately one atmosphere was measured.

The above study also included the irradiation of two organic fluids adsorbed on vermiculite. The gas evolved in these irradiations was mainly

hydrogen with small amounts of carbon dioxide and methane. Here no equilibrium pressure was reached with either fluid and the G values varied with dose rate. This indicates that higher pressures from dissociation may be expected from the radiolysis of organics than from water.

Figure 1 shows the estimated dose rate over a 10-year period for the assumed source term from light-water reactor waste described above. This shows that the dose rate is less than that which would be expected to produce a significant overpressure of hydrogen from the radiolysis of water in concrete. The estimated dose for a period of 10 years is shown in Figure 2. This is well below those anticipated to cause significant damage to any of the waste forms under consideration. However, it is reasonable to believe that in isolated cases low-level waste forms may be generated (by incineration or other volume reduction methods) with specific activities significantly greater than what is cited here as typical. If wastes had activities of tens of millicuries per gram and have dose rates over 10^4 rads/hr, they may produce exposures in the order of 10^9 rads in 10 years. At this higher dose, the gas produced by radiolysis can approach the pressure limit of some containers and the total dose may cause some degradation of the matrix in 10 years. Levels of hydrogen produced by radiolysis can reach potentially explosive mixtures with contained air but is not a major concern with small void volumes and the lack of ignition sources. The radiolysis of chlorinated hydrocarbons (PVC) can release chlorides which may promote corrosion of internal surfaces of the containers.

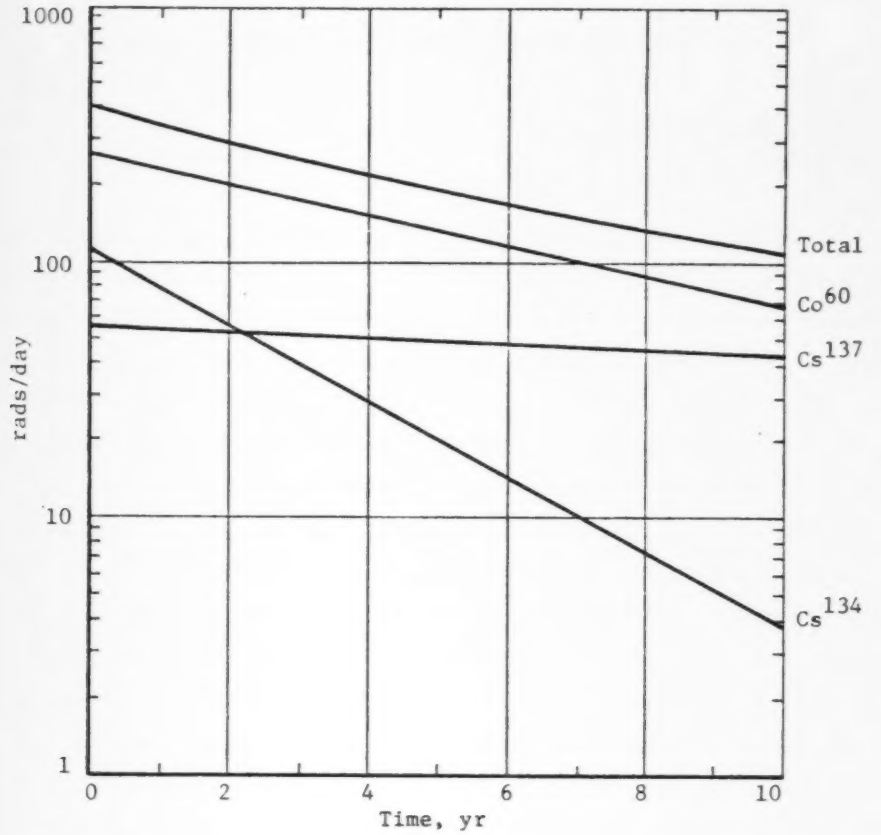

FIGURE 1. APPROXIMATE DOSE RATE IN WASTE CONTAINERS WITH 4.7 μCi/g Co^{60}; 3.3 μCi/g Cs^{137}; 2.00 μCi/g Cs^{134}

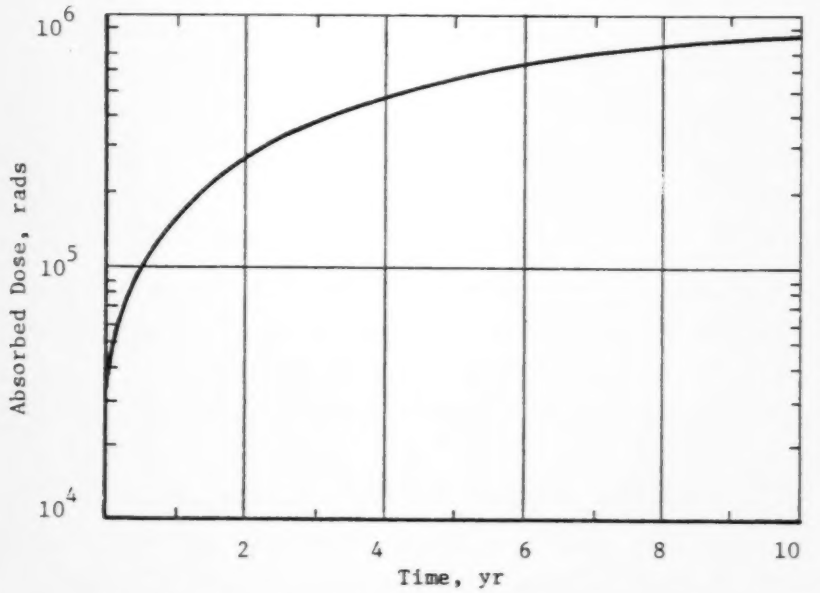

FIGURE 2. APPROXIMATE DOSE ABSORBED IN WASTE COMPOSITES 10 μCi g^{-1} in 55-gallon drum, mixed Co^{60}, Cs^{137}, Cs^{134}

3.3 Structural Effects of Waste Containers

Structural Characteristics of Waste Containers

A definitive analysis of the structural properties of waste containers is beyond the scope of this study, and with such a variety of containers in use, only a general discussion is appropriate. As discussed previously, the general structural standards for containers for shallow land burial result primarily from the DOT and NRC regulations[7,8] for safe transport of the materials with possibly some additional requirements imposed by the waste generating or waste burial operators. For low specific activity wastes, the container structural requirements may be limited to the general requirement for strong, tight packages. A container for burial which is also an approved Type A packaging must retain its contents and effectiveness of packaging when exposed to the defined normal conditions of transport (49CFR 173.398). From a structural standpoint, the most severe of these conditions is usually considered a free fall of four feet onto a flat unyielding surface or the penetration resistance from a 13-pound, 1.25-inch-diameter bar falling 40 inches with its axis perpendicular to any surface. Whereas a Type B container must meet additional more stringent requirements, these containers would seldom, if ever, be used as the disposal container. Rather, a waste container for greater than Type A quantities is transported in Type B packaging but removed for burial. This type of waste container may not have the structural capacity of Type A packaging.

The structural requirements for containers for ocean disposal are better defined. The guidelines[14] state that the packaging should retain the contents until after it is deposited on the ocean floor. Here the major concern is the collapse of the container under the increasing hydrostatic pressure during submergence. The container is assumed to be unable to sustain the stress of the pressure and must either be supported by incompressible contents or the container must leak to equalize the pressure to avoid excessive stress.

Inasmuch as the 55-gallon drum is the most commonly used container for waste disposal, the structural capacity of this container is pertinent. The DOT 17-H steel drum specification defines the type of material, thickness

for side wall and heads, design of closures (bolted head ring or threaded plugs), minimum number and location of rolled or stamped hoops or corrugations, and type of seams. These specified features largely define the structural capability of the drum. In addition, the specification requires the producer of the drum to perform tests on a drum taken at random from production every four months. The drum is to be closed as for use and experience the tests without leaking. The tests include dropping a water-filled drum from a height of four feet onto a concrete surface in a manner to impact on its chime or circumferential seal. Also, the drum is to sustain a hydrostatic pressure of 15 psi for 5 minutes. (A specification DOT 17C drum has a thicker side wall and requires a pressure test of 20 psi for a removable head, or 40 psi for a fixed head drum.) Hydrostatic testing by BNL[38] show that whereas these leak tests may be achievable, they are not necessarily routinely obtained. Recognizing this, some users have specified more frequent testing in their orders as a condition for acceptance.

These specifications are intended to assure some minimum degree of integrity for packaging during transport but there is no obvious assurance of acceptable performance as disposal packaging. The structural loads which a disposal container is expected to experience are largely those which occur from differential pressures or those from impacts. Internal pressures may result from radiolytic decomposition of the waste, but as discussed previously this will require higher radiation levels than expected in most low-level waste containers. Internal pressures may also be caused by physical or chemical reactions within the contents. For example, the swelling of resins upon exposure to water has been reported[39] to cause stresses which have pulverized the concrete matrix and burst the container. Structural loads from external pressures may be most significant during the disposal process for land burial as well as sea burial. For ocean disposal, the hydrostatic pressure is the dominant structural load to the container. For shallow land burial, the weight of the back fill soil plus the weight of backfilling equipment may cause loads of a few 10's of psi on the containers. Although these structural loads from differential pressures may be significant, more structural damage should be expected from impact loads.

The DOT specification 17C or 17H drum is required to sustain a drop of 4 feet onto concrete without leaking. With the small design margin which can be expected for such containers, we may assume that if they are subjected to greater impact loads they will suffer sufficient damage to leak. It can be shown by calculations that a water-filled large container (170 ft^3) with up to 1/4-inch-thick walls or a water-filled 55-gallon drum will be punctured by falling less than 4 feet onto a fixed steel post with a diameter of up to 8 in. unless the contents absorb a large part of the impact energy. These statements are intended to place in perspective the magnitude of structural loads from impacts which may be expected to cause the failure of a container.

It must be recognized that during disposal by land burial most containers will be dropped from heights greater than 4 feet unless they are individually, or in small lots, lowered into position in the burial trenches. It does not mean that every container dropped from greater than 4 feet will fail. It does indicate that waste containers dropped from 20 to 30 feet and impacting on a solid object such as another container will have a high probability of failing, or causing another to fail. During a discussion at a recent conference[40] it was stated that in some operations approximately half of the containers were ruptured during the disposal operation. This is not a criticism of disposal operations since by present objectives the container has completed its role when buried and no further retention is required of it.

In summary, it is evident that waste disposal containers are very susceptible to structural damage which can cause them to fail during or after the disposal operations. If a container is dropped so that it impacts a solid surface or another container, it can burst or puncture. Normal handling operations may scrape through protective coatings exposing bare metal to pitting-type corrosion after disposal. Small dents in a container may result in accelerated stress corrosion after disposal. The loads from the weight of backfill soil and a bulldozer on a burial trench may crush a container wall which is not supported by the contents. Higher than average specific activity in the waste can produce internal pressure by radiolysis to cause a container to leak.

Observed Structural Performance of Waste Packaging

The conclusions of these assessments of the effects of corrosion, radiation damage, and structural damage are largely supported by the inspection of containers after extended periods of burial. Dyer[5] reports on the observed conditions of 55-gallon steel drums 21 to 23 years after disposal on the sea bed at 3000 ft depth. The most common mode of failure was hydrostatic crushing of the drum as wastes had been compressed; there was no evidence of pressure equalization devices. All drums showed evidence of surface corrosion but the metal was generally sound; black sulfide deposits indicated a deficiency of oxygen in the region. Drums which had been breached showed greater deterioration as corrosion could occur internally and externally. The reports[1] of the condition of packaging retrieved from shallow land burial in Idaho show that drums which had been buried in a stacked array for up to 18 months were in generally good condition although some had leaked. Barrels buried from 3 to 7 years by random dumping into the pit showed damage that had occurred during dumping and evidenced contamination levels one order of magnitude higher than from those buried for 18 months by stacking. Barrels buried for 12 years by stacking in pits were in poor condition due mainly to corrosion. A plywood box buried for 5 years was in poor condition; cardboard boxes buried 7 years had disintegrated. In other drum retrieval operations at Idaho[41] it was reported that all drums recovered after 5 to 6 years of burial showed visible rusting of the surface but less than 2 percent were observed to be breached or were without lids. Observations during retrieval operations at Savannah River[42] have led to the conclusions that cotton cloth, paper, and wood buried in water-unsaturated soil at that site will require decades to completely decompose. It is believed this low rate of decomposition results from a deficiency of oxygen.

In summary, these discussions and observations show that little benefit can be expected in the retention of low-level wastes after disposal by the containers which are presently in use. If the container survives the structural loads imposed in handling and burial operations, its life in the disposal environment will be limited to a few years by corrosion. Radiolytic effects to the contents will be a secondary effect in the life of the container.

4.0 TYPICAL LOW-LEVEL WASTE PACKAGES

Four waste packages have been identified as typical of current practices and are presented here for discussion. One package representative of those for sea burial and three systems for shallow land burial are described in Table 1.

TABLE 1. DESCRIPTION OF FOUR TYPICAL WASTE PACKAGES

Package	Container	Coating	Liner	Matrix	Waste Type	Burial Mode
A	55-gallon Drum (DOT 17C)	Paint	None	Bitumen	PWR Filter sludge	Ocean disposal
B	55-gallon Drum (DOT 17H)	Paint	None	Cement	BWR Evap. "bottoms"	Shallow land
C	Large, 178 ft^3 Steel Container	None	None	None	PWR Resins	Shallow land
D	Fiber Drum	None	Polybag	None	Trash	Shallow land

It is believed that there will be a large degree of commonality in the performance expected of these packages when exposed to their respective disposal environments. Package A is believed typical of those recently disposed of by deep sea burial by the European Community. The bitumen matrix with up to 50 volume percent waste would offer an incompressible support for the drum container; this would be classed as a monolithic package and would not require a pressure-relief device. The monolithic design will be more resistant to structural damage during all handling operations than a container with compressible contents. The specific activity of the waste should be less than that which would cause radiolytic deterioration of the matrix for extended

periods. Although corrosion rates may be low and allow long container life (over 20-year life times have been observed), other corrosion data, Section 3.1, would indicate that loss of containment could occur in a short time period (four years or less).

Package B is typical of much of the low-level waste disposed of by shallow land burial. Cement or concrete is a commonly used matrix for solidification, fixation, and/or shielding; it may contain 25 volume percent waste. Some excess water may be released from the matrix and be an available internal corrodent. The steel drum container gains structural support from the concrete matrix and is less vulnerable to puncture. In the event of severe damage during handling, such as loss of the cover, the matrix will limit dispersal of the waste to the atmosphere. The container life after disposal will be limited to a few years or less by corrosion. The paint will not be effective in promoting the container life; whereas general corrosion may be reduced, localized pitting may be accelerated. Upon loss of containment, radionuclides will be available to be leached from the matrix and released to the soil.

Package C is representative of newer systems being used to dispose of large volumes of waste from commercial light water power reactors. The large container is made of mild steel by welded construction and may have a 1/4-inch-thick wall. The ion-exchange resins are assumed to be loaded into the container by being combined with enough water to form a slurry capable of being pumped. After filling, the excess water is removed from the container by draining or by being pumped out through a dip tube. This container will be transported in a Type B overpack which will offer it protection from structural damage during this phase. However, the contents do not provide the rigid support of cement or bitumen and the container will be more susceptible to damage by localized impacts. Although it has a heavier wall, the larger surfaces and greater total weight give it only slightly more resistance to puncture than the thinner wall steel drum with similar contents. After burial, with other factors being equal, the life of the thicker walled container should be proportionally longer than a thin-walled container. The lack of paint or other coatings will permit general corrosion, but will not encourage localized pitting. The damp contents may promote corrosion of the internal surfaces, particularly if the pH is low, but depletion of oxygen in a sealed container may limit the reaction. After loss of containment, the large surface area of the contents will promote release of the radionuclides to the soil.

Package D is representative of a class of packaging which would include wooden and cardboard boxes as well as fiberboard drums. These are more typical of low-level waste packaging at government laboratories which also operate a burial ground. Where public transportation systems are not required, the waste packages may be carried in a dumpster from a lab area where they are packaged and dumped directly into a burial pit. The trash waste includes contaminated paper, rags, plastic tubing, glassware, tools, etc., which are collected in a plastic bag. The bag is taped closed prior to being inserted into the fiberboard drum. The drum is then sealed with tape. The light weight and small size of the containers make them less sensitive to structural damage than large containers although they may be punctured by sharp objects. The life of these containers after burial is expected to be short, several months to a few years, depending upon soil conditions. However, the plastic bag may retain the contents for longer periods.

5.0 RECOMMENDATIONS

There is an increasing involvement of Federal agencies in low-level radioactive waste disposal as well as the management of all nuclear wastes. A DOE Task Force[43] has recommended that DOE assume the responsibility for the management of the six commercial waste burial grounds in addition to the Government-owned sites in order to strengthen technical capabilities and operating practices by the application of research and development, and to develop criteria for carrying out responsibilities of the program. An NRC Task Force[44] has concluded there is an urgent need to establish standards, criteria, and regulations governing low-level waste management. The EPA[45] has taken initial steps to recommend environmental protection criteria to be used for the development of environmental standards for radioactive waste management. Somewhere in this evolving process it will be necessary to establish criteria for the performance of the packaging for low-level waste disposal and regulations and standards can then be developed to meet the criteria. It is apparent that there is presently a void in the general control of low-level waste packaging. However, to fill this void with practical and effective controls will require a significant study effort. Extensive further research is needed to define the mechanisms for transport of various nuclides in specific shallow land burial environments, to define optimum waste forms which will be long lived and limit mobility of the wastes, and to specify packaging which will maintain its integrity through the stresses imposed by the disposal operations and will have a low rate of corrosion to allow long container life. More information is needed to describe the relative roles of the burial soil (or ocean bottom), the waste form, and the packaging as barriers to the transport of radionuclides. It can only be through a better understanding of these roles that a cost-effective approach can be made to limiting the migration of nuclides. The economics of waste disposal will always be a consideration as it is the general public who must ultimately pay the cost.

Improved packaging must consider all aspects of the problem including the waste composition, the final waste form, the container structural design, the container materials, the handling operations, the burial environment, the desired performance of the total system, and the

acceptability of the cost. The following areas are recommended for consideration.

(1) The packaging can be more effective if the material to be contained is defined. There is need to classify the wastes according to the nuclide content for effective containment. This classification among other things, should consider half-life, mobility, and the imposed risk to the environment. For example, tritium, or tritiated water, may be considered a class by itself because of high mobility and great abundance as a waste product so that special barriers may be utilized to restrict its entry into the environment. Also, different barriers would be effective for fission or activation products with half-lives of several years than for I^{129}, Cs^{135} or some actinides with half-lives of thousands of years.

It must be recognized that wastes are not produced in convenient classes but are usually complex mixtures. Although it may be possible to segregate various nuclides in some waste collection processes, segregation may be impactical or uneconomical in most processes. In the latter case classification of wastes may be necessary on the basis of the dominant characteristic of the mixture. For example the waste may be classified on the basis of the longest half-lived or most environmentally hazardous component with some consideration for relative concentration.

(2) An effective barrier to migration is the form of the waste. Increasing degrees of inertness or insolubility of the waste form will tend to decrease mobility. Certainly a solid waste form is less mobile than a liquid and whereas solidification of wastes is a general requirement, there should be a better definition of acceptable solids. If absorbed liquids are to be permitted, there should be a better definition of acceptable absorbents, and acceptable liquid/absorbent ratios. Preferably all wastes will be solidified by removal of the liquid phase, or chemical binding of the liquid. Currently, cement, plaster, bitumen, and polymerized resins are used as a matrix for solidifying wastes. These same materials are also used for fixation of dispersable solids. Although studies are in progress to characterize various formulations of these materials, more efforts should be applied to the study of solidification or fixation agents to define acceptable materials and relative quantities of waste in the matrix to achieve optimum thermal, radiolytic, and structural stability of the waste form. Consideration should

also be given to placing a barrier between the solidified waste and the container such as bitumen, plastic, or metal to further encapsulate the waste and to reduce internal corrosion of the container. Compatibility of the waste form with the container should be a major consideration.

(3) Within the present approach to low-level waste management, the burial trench provides the dominant barrier to nuclide migration and the relative role of the container should be evaluated in respect to the soil. The life of the waste container will be affected by the soil conditions which may either accelerate or retard corrosion. Compatibility of soil conditions and container materials should be a large influence on site selection. The soil conditions for shallow land burial sites should be well characterized to permit container materials to be tailored where possible to be compatible with the soil. Conversely, the trench environment may be modified to be more compatible with the waste package. Water flow in or out of the trench may be restricted by lining the trench with plastic, metal, concrete, asphalt, or by more natural materials such as impervious clays or capillary barriers of fine and coarse sand layers. Entrance of surface waters into closed trenches may be limited by contouring, tiling, paved caps and ground cover. It may be desirable to affect the chemistry of the soil, such as adjusting the pH by the addition of alkaline materials. Whereas many of these materials may be considered effective for only short terms, they may be beneficial for limiting migration of nuclides with short half-lives.

(4) With an understanding of the degree of retention of nuclides that may be achieved with the waste form and the burial trench, it may be more practical to evaluate the benefits that may be achieved with improved container life. Ideally, the life of the container will be as long as the waste remains a hazard to the environment. Practically, however, this may not be achievable except for wastes with half-lives up to a few years. (A factor of 1000 reduction in concentration requires a period equal to 10 half-lives.) Defining methods for dependably extending the life of the container will require extensive studies. One requirement is to assure that the container is intact and free of damage when the burial procedure is complete. An initial step is to develop improved seal designs, materials, and methods to achieve a high probability of sealing the container when it is closed, or to routinely leak test each container. Next, the structural capacity of

the packaging must be able to sustain the loads applied by the handling and burial process. This will require achieving an optimum balance between increased strength of the package and more control of handling operations to reduce normal stresses on the package.

After burial, corrosion becomes the dominant effect upon the container life. We have previously suggested that some control of the trench environment or the waste form can affect the rate of corrosion; however, it is recognized that the container design and material dominate the corrosion rate. Much effort has been applied to studying the corrosion of metals in soils, particularly in respect to steel pipes. Whereas, it is recognized that some materials, such as stainless steel, show much better performance than mild steel, their high cost has been a deterrent. Greater attention has been directed to the effect of coatings. Coatings of paint, epoxy resins, and asphalt or bitumen have been commonly used but are relatively ineffective because of the difficulty of avoiding localized scratches and scuffs from handling. The value of these coatings may be improved by making the final application immediately prior to the burial process. More tenacious coatings of dipped metal (galvanized), plated metal, or impervious oxide are more effective, but higher in cost. Some benefits have been observed from the use of sacrificial anodes. However, further study is required to define dependable life times for containers utilizing various approaches for this application. The benefits to be gained by improved container life can then be evaluated in terms of increased container costs to assist in selecting more effective packaging. The final result should lead to a few standard container designs which can result in sufficiently large production to lead to more economical manufacturing of dependable containers.

(5) The real benefits from improved waste forms, container designs, and burial operations can be measured only by monitoring their performance in service. Although environmental monitoring is presently being conducted at disposal sites, its purpose is to perform surveillance of the site performance. It is recommended that improved techniques, including continuous environmental monitoring be conducted to evaluate the effect of various factors in the migration of nuclides. This experimental effort will then be effective in evaluating improvements in the barriers to migration as they are implemented.

(6) In summary, it is recommended that criteria be developed for the required retention of various classes of radionuclides for environmental protection. Within that scope, the potential roles of different barriers should be defined. From this base criteria may be developed for each of the barrier systems, i.e., waste form, packaging, etc. Standards and regulations can then be developed in response to these criteria.

Acknowledgments

This report was compiled by Neil E. Miller of Battelle Columbus Laboratories, BCL, with significant contributions made by

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Warren E. Berry, BCL
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